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SIMULATION OF CLOSED CHAMBER BURNING OF VERY-HIGH BURNING RATE PROPELLANT

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JULY 1988

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

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Closed chamber firings of very-high burning rate (VHBR) propellants have been conducted at the Ballistic Research Laboratory as part of the traveling charge gun program. Using standard closed chamber data reduction techniques, burning rates in the range of 10 to 300 m/s over a pressure range of 50 to 300 MPa have been measured. Pressure-time records from the firings of VHBR propellants exhibit severe pressure wave phenomena which are removed by digital filtering prior to transformation to burning rate data. Burning rate data for four VHBR propellants were used in a 1-D traveling charge code set up to simulate VHBR propellant being fired in a closed chamber. Objectives were to check consistency of the data, obtain better estimates of the data, obtain an understanding of the gas dynamic phenomena occurring in the chamber, and assess the validity of simulations produced by the

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19. ABSTRACT (CON'T)

1-D traveling charge gun code. The procedure used was to match simulated data to experimental pressure-time data and adjust the burning rate data until the two curves matched. Two of the propellants which had burning rates less than 35 m/s over the 50-150 MPa pressure range were simulated successfully with only minor adjustments in the burning rate data. Simulation failed for a propellant with a high burning rate of 55 m/s at 50 MPa because of rapid transition to super-sonic burning. The fourth propellant, characterized by a steep burning rate slope and a burning rate of 146 m/s at 150 MPa, was simulated with difficulty, obtaining only fair agreement between simulated and experimental pressure-time curves. It is concluded that consistency of burning rate data in excess of 35 m/s over the pressure range of 50-150 MPa is poor. High amplitude pressure waves in the chamber create severe errors in the derived propellant burning rates. Transitions to supersonic burning in the simulations indicate that the assumption of a thin combustion zone used by the 1-D traveling charge gun model may be suspect and should be replaced with a more realistic combustion model.

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I. INTRODUCTION

Closed chamber firings of the very-high burning rate (VHBR) propellant used in the traveling-charge gun firings conducted at the Interior Ballistics Division of the Ballistic Research Laboratory produce pressure-time records characterized by very rapid pressure rise (20 μs or less) and severe pressure oscillations. A typical record is displayed in Figure 1. To transform these records to propellant burning rates, Juhasz and others,[1] used digital filtering techniques to remove the pressure oscillations from the data producing "smooth" pressure-time records typical of normal slow burning propellant prior to using standard techniques to reduce their smoothed data to burning rates. One of the basic requirements for standard closed bomb burning rate analysis is the absence of pressure waves.

The VHBR propellants are porous so the term "apparent" burning rate has been defined to characterize the combustion of these propellants in contrast to the term linear burning rate used to characterize the normal solid propellant. The apparent burning rate r is defined by the relation:

$$r = \frac{\dot{m}}{\rho_{P_o} S} \tag{1}$$

where:

$\dot{m}$ - propellant mass burning rate

ρ_{P_o} - porous propellant bulk density

S - surface area of end burning propellant grain (assumed to be constant)

There is some question that burning rates produced using the above techniques truly represent the apparent burning rates of the propellant. The objective of this paper is to (1) check the consistency of the VHBR data; (2) obtain better estimates of the VHBR data; (3) obtain a better understanding of the gas dynamic phenomena occurring in the closed chamber; and (4) assess the validity of the simulations produced by the 1-D traveling charge gun code.

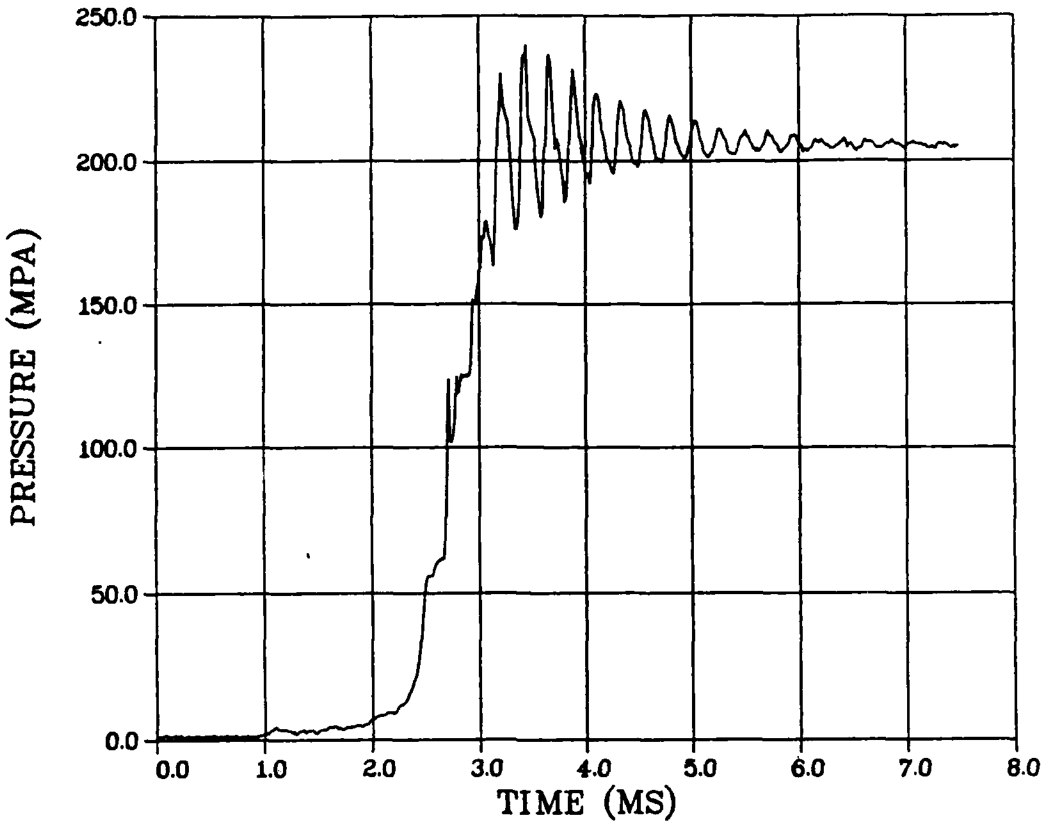

Figure 1. Experimental Pressure-Time Curve 29-51A Mod 7 Propellant

II. PROCEDURE

Data from the closed bomb firings of the VHBR propellant consists of the unfiltered and filtered pressure-time data; the results of reduction to burning rates; and graphical log-log plots of burning rates vs pressure. Together with this data are information on the geometry of the interior of the closed bomb including the location of the end-burning VHBR propellant and the location of the pressure gauges. A diagram of the bomb used to test 36 mm VHBR samples is displayed in Figure 2. The sample chamber is 40 mm in diameter by 142 mm long. The propellant samples are 36 mm in diameter by 25.4 mm long. The samples are inhibited on the side and enclosed in a thin steel sleeve. The pressure gauge next to the propellant sample is 10 mm from the end of chamber. Data from this gauge were recorded but not used since the steel sleeve masked the pressure gauge port creating errors in the magnitude of the recorded pressure. The other gauge is 2.5 mm from igniter end of the

chamber; so the distance between this gauge and the burning propellant surface varied from an initial value of 114.1 mm to 139.5 mm at propellant burnout. Other data consists of the propellant density, mechanical properties (when available) and thermodynamic properties as computed by the BLAKE[2] code.

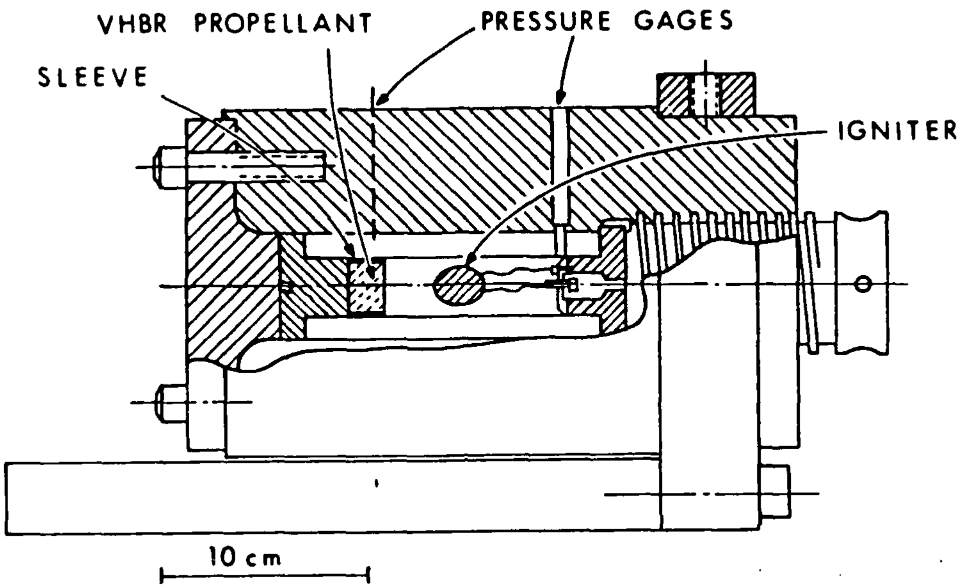

Figure 2. Closed Chamber for VHBR Propellant

Given the above data, the procedure was to:

1. Use the 1-D traveling charge code,[3] which had been developed to model the firings of a traveling-charge gun, to simulate the firing of the VHBR propellant in a closed bomb. In the closed bomb simulation, motion of the projectile and charge was suppressed by using a shot-start pressure greater than the expected maximum projectile load pressure (gas pressure plus thrust pressure from the burning propellant). A table of propellant burning rates vs pressure from the closed bomb data reduction was used as initial estimates.

2. Adjust the propellant chemical energy values as computed by the BLAKE code until the maximum pressure produced in the simulation matches the experimental maximum pressure from the closed bomb firing. Using the BLAKE data in the simulations gave higher maximum pressures than was measured, so

the computed chemical energy had to be reduced. The computed and adjusted chemical energy values for the four VHBR propellants used in this study are given in Table 1. The formulations are described in more detail by Juhasz.[1]

TABLE 1. Computed and Adjusted Chemical Energy Values for VHBR Propellants

Propellant Name	Computed Chemical Energy J/g	Adjusted Chemical Energy J/g	% Change
1086-7B	4458	4002	10.2
29-51A M7	4918	4918	0.0
30-4A	5044	4233	16.1
1086-8A	4259	3524	17.3

The reason for the adjustment is discussed in reference 1 and is believed to be due largely to a chemical kinetic effect as well as to a lesser extent heat loss which delays the complete chemical reaction until after maximum pressure is reached in the bomb.

3. The pressure-time curve at a pressure gauge location is produced by the simulation and this curve is then compared to the corresponding experimental pressure-time record. If the two curves compare within the experimental error, then the burning rate data obtained from the closed bomb data reduction represents the apparent burning rate of the sample. If the two curves do not agree, then the burning rate vs pressure data is adjusted, the simulations being repeated until agreement is obtained. The adjusted burning rate data then represents the apparent burning rate of the sample.

III. TRAVELING CHARGE GUN CODE CHANGES

In the traveling charge code the burning rate r is expressed in a functional form of:

$$r = a + b\,P^n \tag{2}$$

where a is the burning rate intercept, b is the burning rate coefficient, n is the burning rate exponent, and P is the pressure. Examination of the VHBR data indicated that it would be impossible to fit the above form over the pressure range of interest. It was decided to read the data in as a table of burning rates and pressures, convert to the log of burning rate and log of pressure, and then interpolate using the pressure in the log-log table to produce a burning rate. Burning rate coefficients and exponents for equation 2 are also computed from this data. To obtain burning rates below or above the experimental pressure range, the initial burning rate coefficient and exponent are used in equation 2 to compute burning rates below the exper-

imental pressure range and the last burning rate coefficient and exponent are used to compute burning rates above the experimental pressure range.

IV. SIMULATION OF VHBR PROPELLANT CLOSED CHAMBER FIRINGS

The closed chamber firings of four VHBR propellants were simulated with the 1-D traveling charge gun code. The burning rates at pressures of 50, 100 and 150 MPa are given in Table 2 with the propellants arranged in order of increasing burning rate.

TABLE 2. Burning Rates for Four VHBR Propellants at 50, 100, and 150 MPa

Propellant	Burning Rate (m/s)*		
	50 MPa	100 MPa	150 MPa
1086-7B	1.4	3.3	10.7
29-51A M7	25.2	34.1	26.6
30-4A	54.7	40.5	53.5
1086-8A	1.1	57.3	146.1

* Data from reference 1, Table 11

The log-log plots of the burning rate vs pressure data for the four VHBR propellants are displayed in Figure 3 (1086-7B), Figure 5 (29-51A Mod 7), Figure 7 (30-4A), and Figure 9 (1086-8A). Two curves are plotted on each graph, the solid line representing the data as obtained from the closed chamber data reduction process. Most of these data were used in the simulations. The dotted line represents the modified burning rate data needed to give a match between the simulated and experimental pressure - time curves.

The thermodynamic data and propellant density used in the simulations are given in Table 3.

TABLE 3. VHBR Propellant Thermodynamic and Density Data

Propellant	1086-7B	29-51A Mod 7	30-4A	1086-8A
Chemical Energy J/g	4002	4918	4233	3524
Specific Heat Ratio	1.2344	1.1790	1.1813	1.2456
Covolume cm^3/g	1.255	1.001	1.018	1.213
Molecular Weight mol/g	18.294	23.841	23.400	18.727
Density g/cm^3	1.399	1.278	1.313	1.443

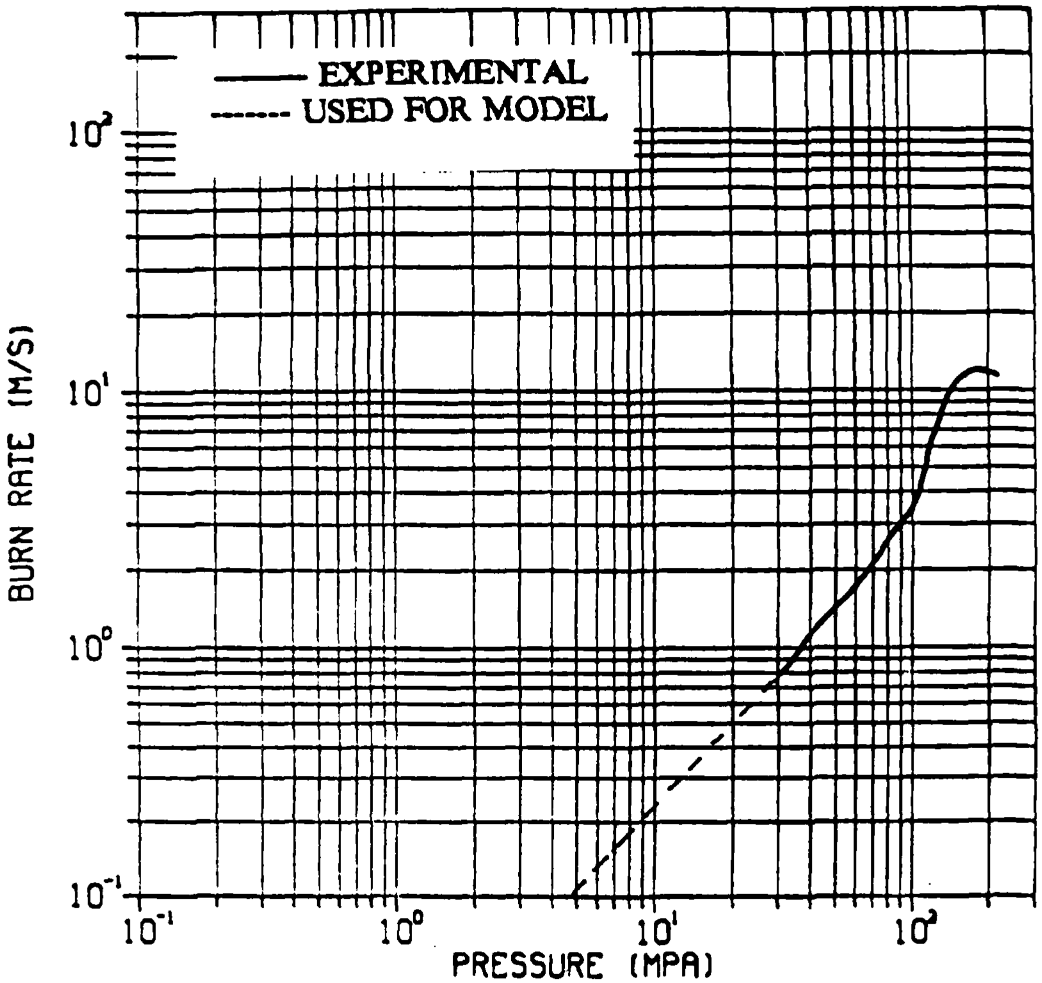

Figure 3. Apparent Burning Rates for 1086-7B Propellant

For the 1086-7B propellant burning rates are given over the 30 to 200 MPa pressure range. The simulation was started at an initial pressure of 2 MPa; so the experimental burning rate data were extrapolated to that pressure level. The simulated and experimental pressure-time curves for the firing of this propellant is displayed in Figure 4. The agreement between the two curves is excellent up to a pressure of about 200 MPa at which time the two curves diverge. No attempt was made to obtain a better match at the high pressure end of the curve. These results indicate that the burning rate data obtained by the closed bomb data reduction process is a reasonable approximation to the apparent burning rate of the propellant. For the 29-51A Mod 7

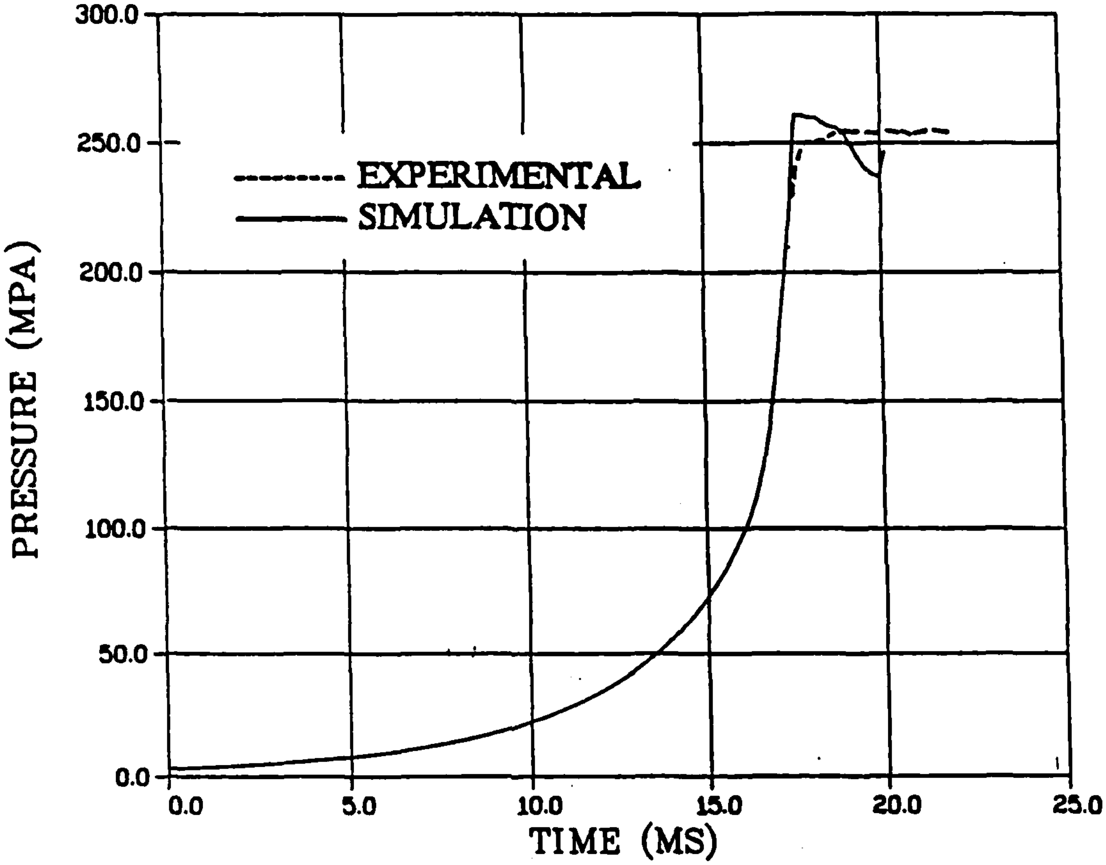

Figure 4. Closed Chamber Pressure-Time Curves Simulation and Experiment for 1086-7B Propellant

propellant, burning rate data are given in Figure 5 over the 20 to 90 MPa pressure range. Like the previous propellant, the starting pressure of 2 MPa required that the burning rate be extrapolated to that pressure. Several extrapolations were tried until one was found which gave the best match between the simulated and experimental pressure-time data. The simulated and experimental pressure-time curves are displayed in Figure 6. Up to a pressure of 140 MPa the agreement is good; above that pressure the agreement is poor. Since the burning rate data derived from the experimental pressure-time data is given only up to 90 MPa, it can be concluded that these burning rate data are reliable up to that pressure. At pressures above 90 MPa, the simulation code assumed that the burning rate data followed a linear extrapolation based on the last two pairs of log burning rate vs log pressure data. This may not represent the actual propellant burning rate curve. No attempt was made to

refine the burning rate data in this pressure regime. It will be noted that the frequency of simulated pressure oscillations matches the actual measured pressure oscillations except that the two curves are out of phase. In conventional propellant closed bomb burning rate analysis, similar trends are seen at both the low and high pressure end. In fact, typically only the burning rates obtained between 20% and 80% of the peak pressure are usable because the propellant grains may be only partially ignited at the low pressure end of the curve and propellant slivering effects predominate at the high pressure end.

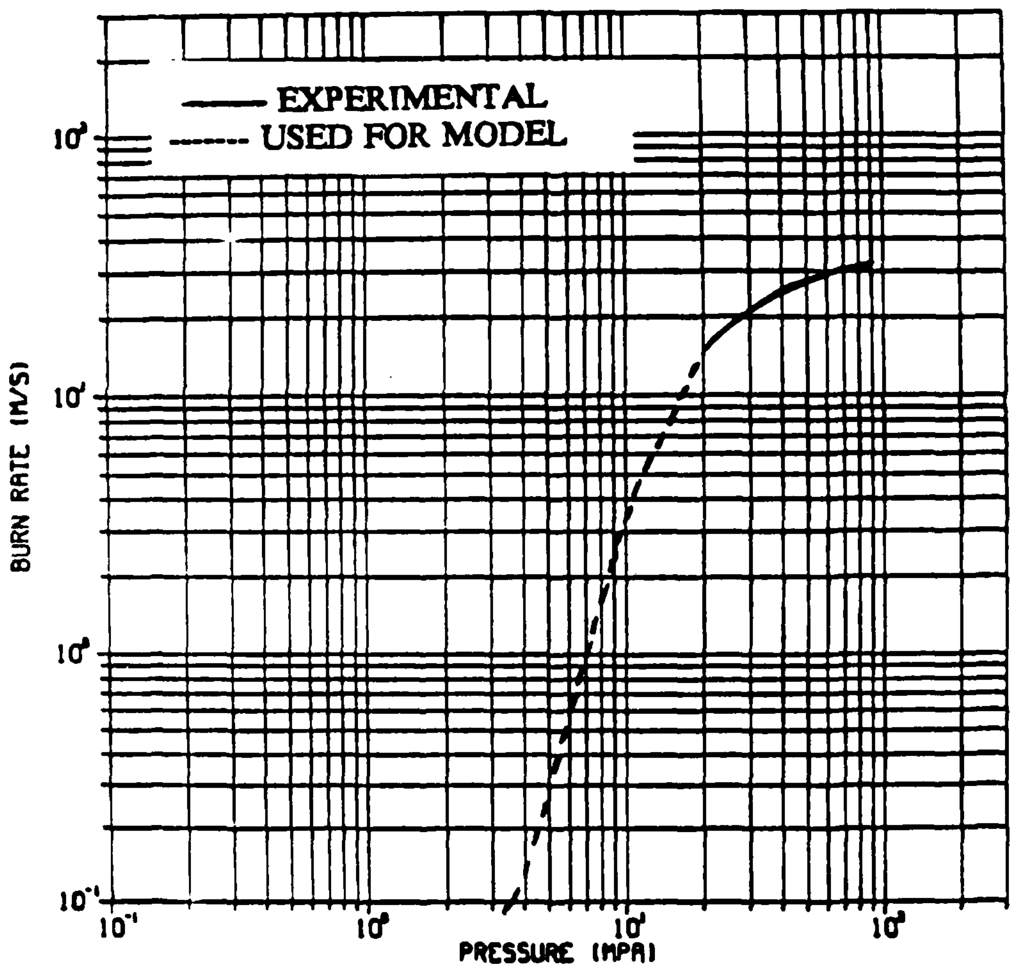

Figure 5. Apparent Burning Rates for 29-51A Mod 7 Propellant

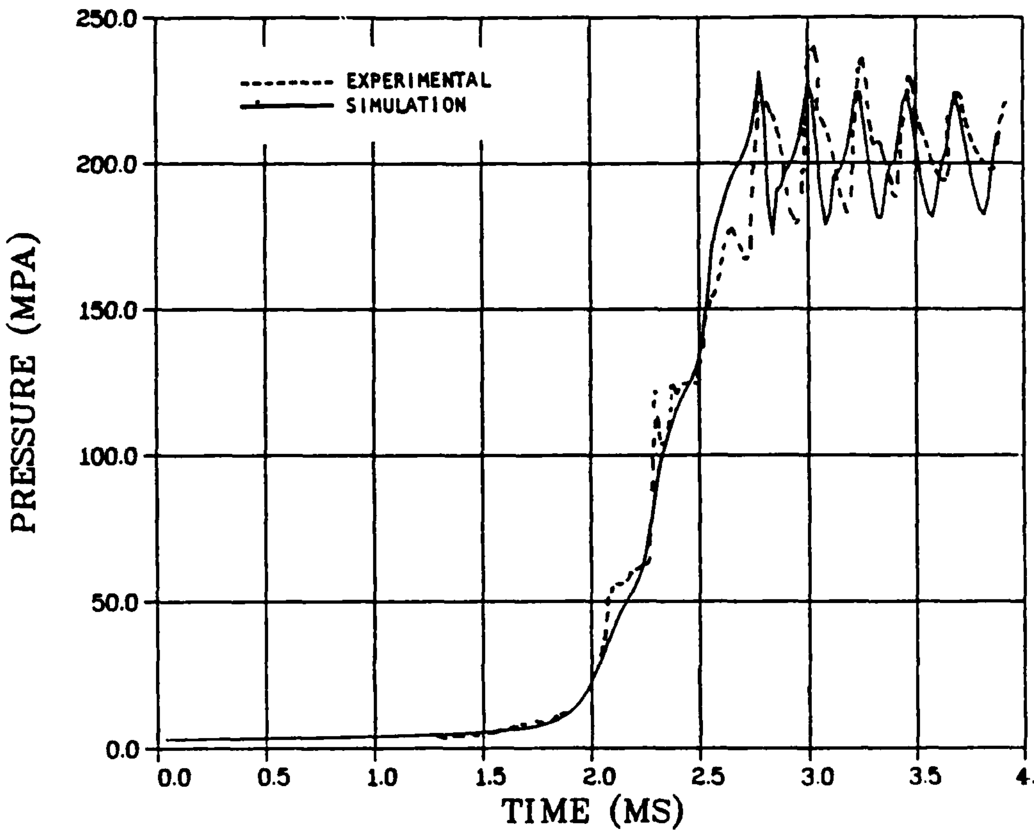

Figure 6. Closed Chamber Pressure-Time Curves Simulation and Experiment for 29-51A Mod 7 Propellant

For the 30-4A propellant, burning rate data are given over the 20 to 150 MPa pressure range as shown in Figure 7. In contrast to propellants 1086-7B and 29-51A Mod 7, the derived burning rate is nearly constant over this pressure range, varying from 40 to 55 m/s. A linear extrapolation of burning rate on the log-log plot to the starting pressure of 2 MPa gives a burning rate of 38 m/s. This when used in the simulation gave an initial supersonic flow of gas from the burning propellant and a constant burning rate thereafter.

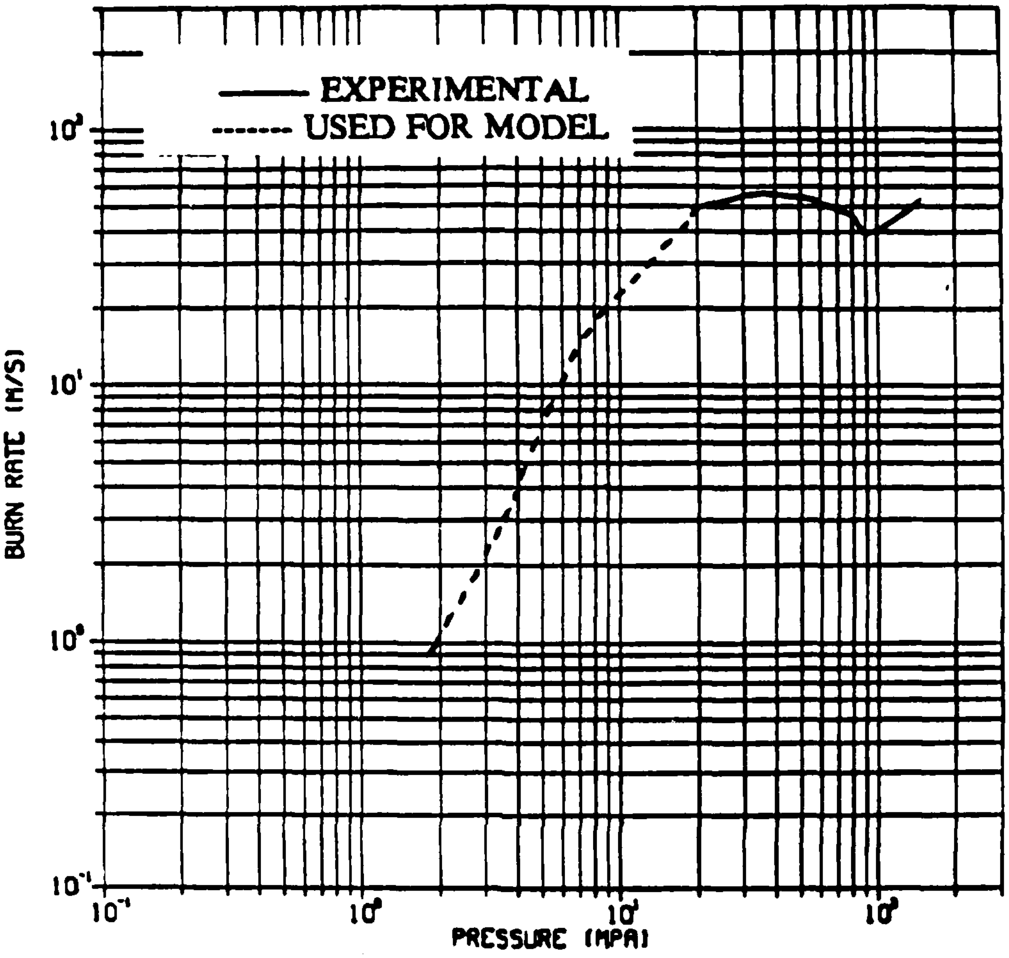

Figure 7. Apparent Burning Rates for 30-4A Propellant

The transition from subsonic to supersonic burning of VHBR propellant is discussed by Gough.[3] If the burning is assumed to be steady and occur in a thin zone, then a strong deflagration wave, i.e. supersonic burning, can be shown to lead to an unstable flame and thus be inadmissible. If the thin combustion zone in the model be replaced with a thick two-phase combustion zone then the possibility of supersonic burning exists. Under such conditions the pressure at the burning propellant surface is uncoupled from the pressure in the gas column and the normal empirical relation between gas pressure and burning rate, equation (2), will no longer apply.

Several attempts were made to extrapolate the derived burning rates down to lower pressures without getting into supersonic burning. The dotted line shows the burning rate data which gave the best agreement between simulated and experimental pressure-time data. The simulated and experimental pressure-time curves are displayed in Figure 8. Both are in agreement up to about 4 MPa after which the experimental curve makes a sharp rise which is not matched by the simulated pressure-time data. The simulation indicated that at 4.2 MPa there was a sharp pressure increase (within 10 μs). At the same pressure there was an rapid increase in propellant gas velocity which increased from an Mach 0.8 to a Mach 1.19. At the same time the burning rate increased from 2.89 m/s to 6.07 m/s after which the burning rate stayed constant since it was in the supersonic burning regime. It was concluded from these results that the simulation code is incapable of modeling the combustion of this propellant.

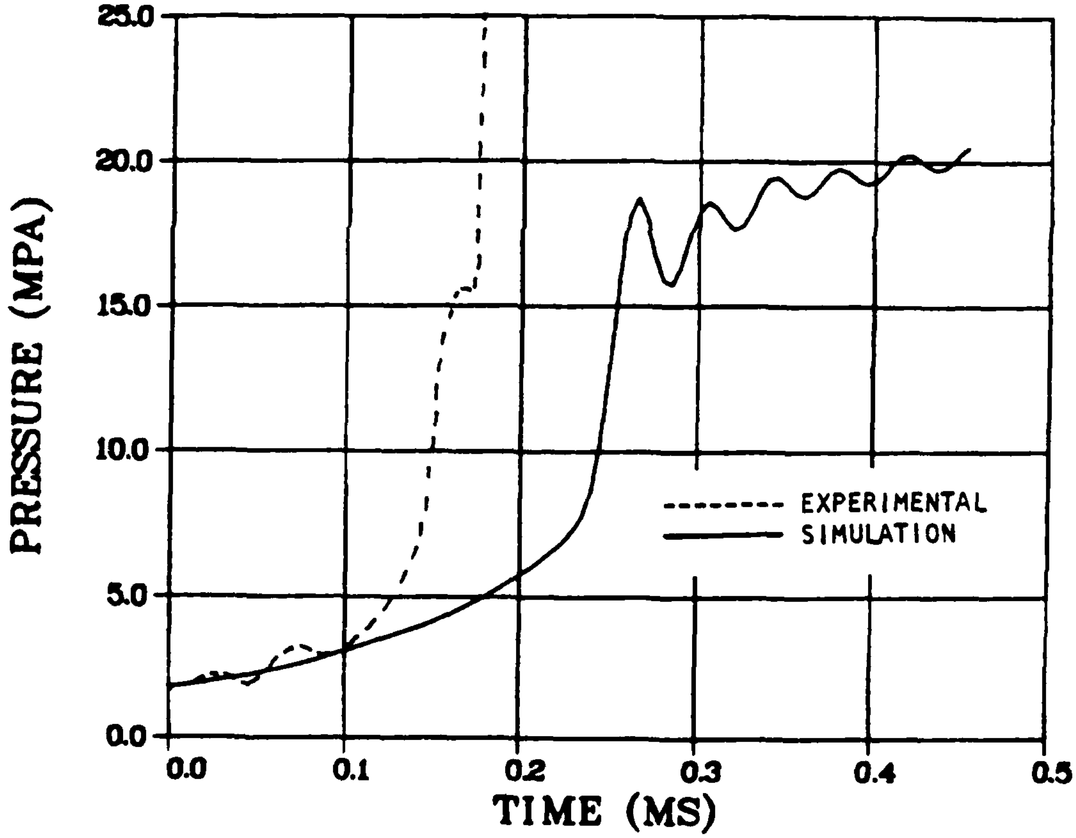

Figure 8. Closed Chamber Pressure-Time Curves Simulation and Experiment for 30-4A Propellant

For the 1086-8A propellant, experimental burning rate data is given over the 35 to 250 MPa pressure range in Figure 9. The burning rate curve has a very steep slope over the 35 to 100 MPa pressure range followed by a gradual decrease in slope in the 100 to 250 MPa pressure range. A linear extrapolation of burning rate on the log-log plot to the ignition pressure of 2 MPa gave a burning rate value approaching zero and thus the simulation code could not get started. It was decided to use the burning rate curve for the 1086-7B propellant for the pressure range starting at 2 MPa and then blend the curve into the 1086-8A experimental curve at a pressure of 50 MPa. These data are shown as a dotted line in Figure 9. A minor lowering of the burning rate data

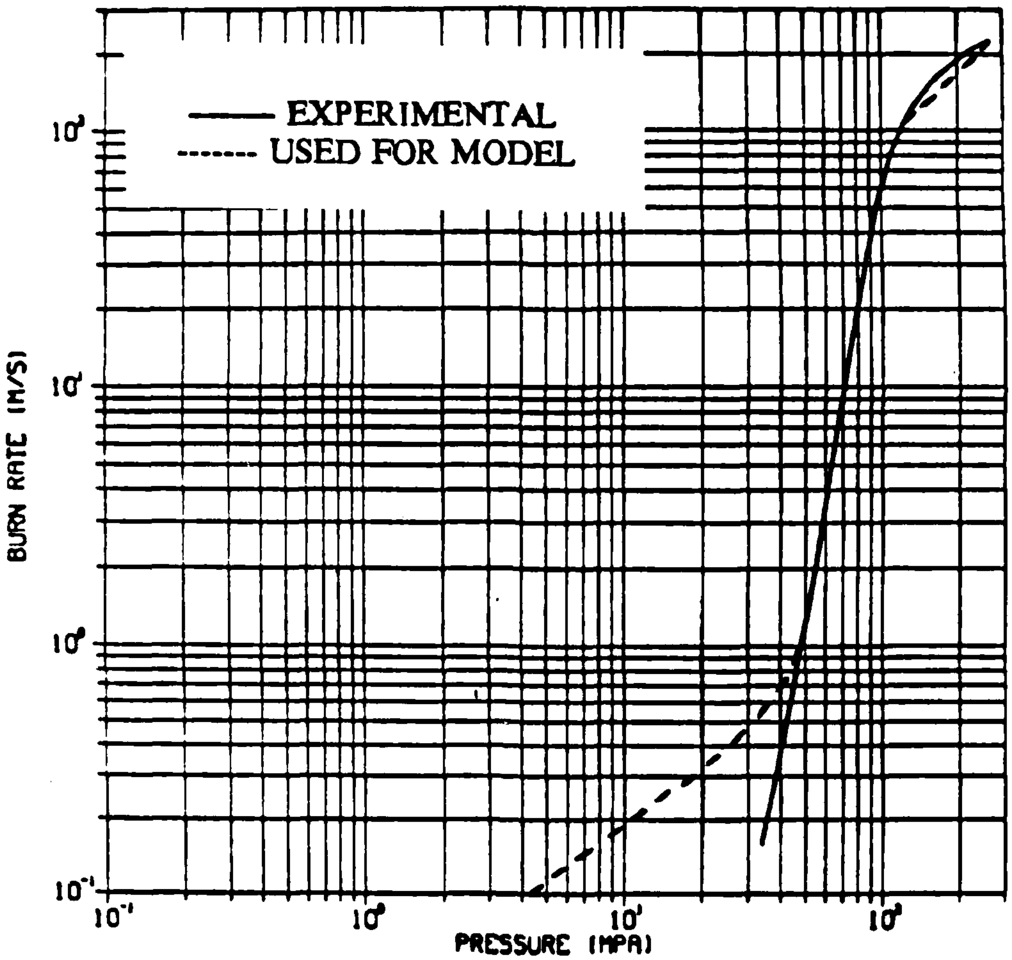

Figure 9. Apparent Burning Rates for 1086-8A Propellant

in the pressure range of 120 to 250 MPa was made in order to keep the gas velocity below the sonic level. The agreement between the experimental and simulated pressure-time curves is displayed in Figure 10. The experimental pressure-time data is characterized by a long slow pressure rise, followed by a rapid pressure rise with many oscillations thereafter. The simulated pressure-time curve follows the experimental pressure-time curve except that the slope of the rapid rise pressure region is not as great as the slope in that region for the experimental data. Frequency of large amplitude pressure oscillations for both the experimental and simulated pressure-time curves is about the same.

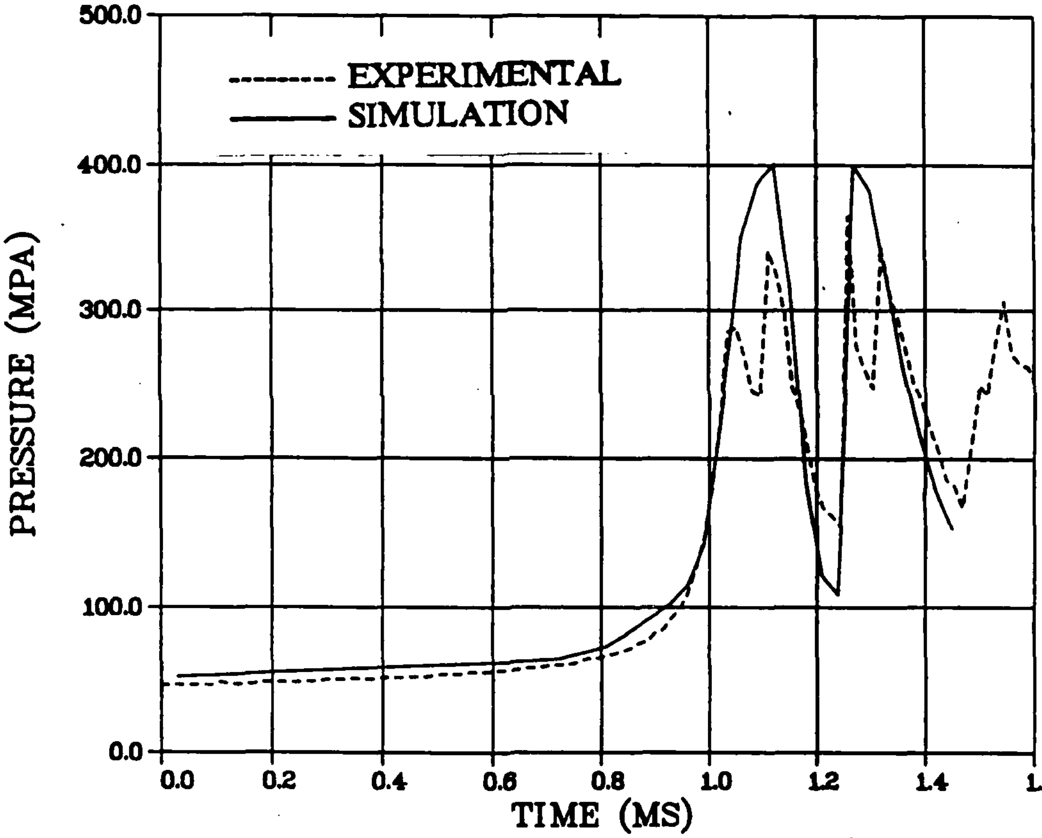

Figure 10. Closed Chamber Pressure-Time Curves Simulation and Experiment for 1086-8A Propellant

The development of pressure oscillations in the closed chamber is illustrated in Figure 11. This is a pair of 3-D plots of pressure as a

function of chamber position and time during the burning of the 1086-8A propellant. Pressure in the burning propellant grain and pressure of combustion gas in the chamber are shown. In the lower plot, details of pressure build-up in the grain (at the 0.14 to 0.15 m position) are shown. Prior to 0.8 ms there is no significant difference between grain pressure and chamber pressure. After that time, increased propellant burning leads to increased thrust on the propellant grain base and increased pressure in the propellant. This internal propellant pressure continues to increase until propellant burnout. The upper plot shows details of pressure build-up in the entire chamber up to the peak of the first oscillation. Burning of the traveling charge increases the pressure at the propellant grain end of the chamber, which then propagates to the other end of the chamber, reflects and then moves back to the grain end of the chamber. Since the pressure gauge monitoring events in the chamber is located 2.5 mm from the igniter end; it would record the arrival of the pressure wave and subsequent reflection off the end wall of the chamber. This plot indicates that the pressure gage does not monitor events at the propellant burning surface but events which are displaced in space, time, and magnitude from the events occurring at the propellant surface.

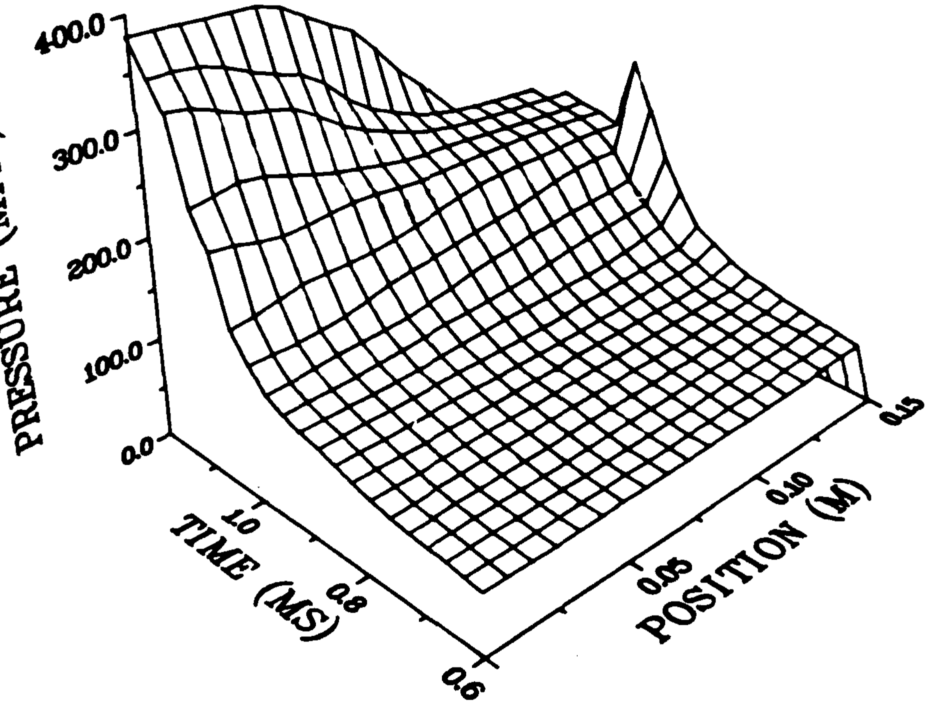

Figure 11a. <u>Simulated Pressure Space-Time Curves for Burning of 1086-8A Propellant</u>

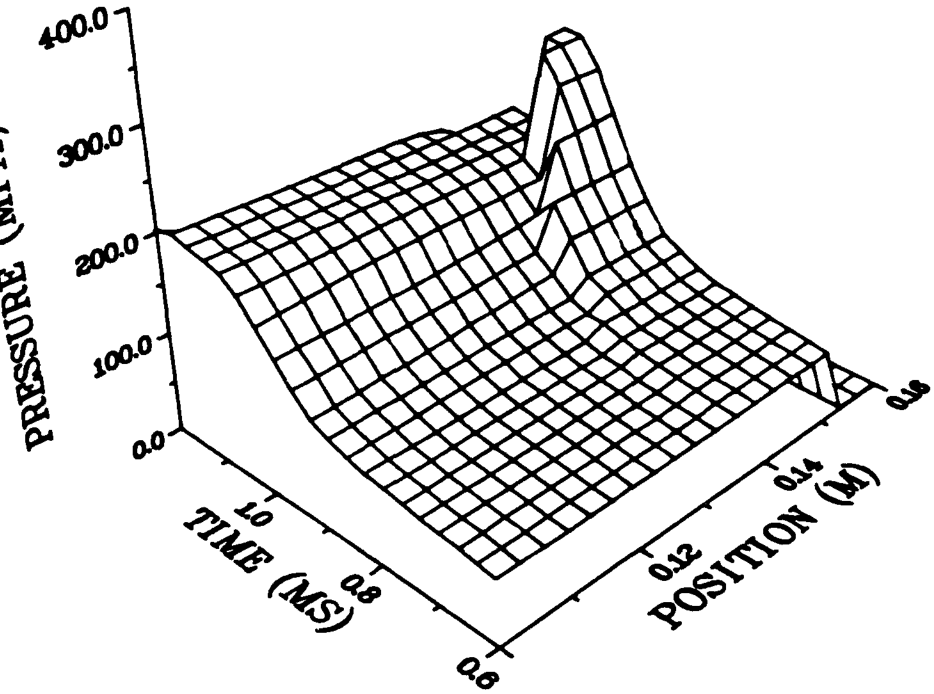

Figure 11b. Simulated Pressure Space-Time Curves for Burning of 1086-8A Propellant

V. DISCUSSION AND CONCLUSIONS

The 1-D traveling-charge gun code has been used to model the burning of four VHBR propellants in a closed bomb. Propellants 1086-7B and 29-51A Mod 7 burned exclusively in the subsonic regime and thus the code was able to predict the pressure-time behavior with only minor changes being made to burning rate data derived from standard closed bomb data reduction. Propellant 30-4A burned nearly exclusively in the supersonic velocity regime, if the burning rates derived by the standard techniques are indeed appropriate. The code was unable to simulate the pressure-time behavior of this propellant.

The simulation of the pressure-time behavior of 1086-8A propellant presented a difficult problem. Using the burning rate data of propellant

1086-7B allowed us to simulate the slow pressure rise behavior up to a pressure of 50 MPa. Use of the modified burning rate data gave fair agreement between predicted and experimental pressure-time data for the region above 50 MPa.

We were successful in modeling the closed chamber behavior of three out of the four VHBR propellants chosen for this investigation. Failure of the code to model the fourth propellant (30-4A) can probably be attributed to a transition from normal convective propellant burning to stress fracture of propellant into small particles and rapid burning of those particles. This phenomena would appear as an apparent transition to supersonic burning. This indicates that the VHBR combustion model used in the 1-D traveling charge code requires modification. A paper by Kooker and Anderson[4] suggests a possible alternate combustion model for the 1-D traveling charge code. In this model there is a transition from normal convective propellant burning to pore compression and propellant break up in depth. The propellant fragments subsequently are entrained in the flame zone forming a two-phase flow combustion process capable of supporting a very rapid increase in pressure. Such a model, when perfected, may eliminate the difficulties encountered in this investigation.

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